Weak Production of Strangeness as a Probe of the Electron-Neutrino Mass

Proposal to the Jefferson Lab PAC

Abstract

It is shown that the helicity dependence of the weak strangeness production process $p(\vec{e}, \bar{\nu}_e)\Lambda$ may be used to precisely determine the electron neutrino mass. The difference in the reaction rate for two incident electron beam helicities will provide bounds on the electron neutrino mass of roughly 0.5 eV, nearly three times as precise as the current bound from direct-measurement experiments. The experiment makes use of the HKS and Enge Split Pole spectrometers in Hall C in the same configuration that is employed for the hypernuclear spectroscopy studies; the momentum settings for this weak production experiment will be scaled appropriately from the hypernuclear experiment (E01-011). The decay products of the hyperon will be detected; the pion in the Enge spectrometer, and the proton in the HKS. It will use an incident, polarized electron beam of 194 MeV scattering from an unpolarized CH_2 target. The ratio of positive and negative helicity events will be used to either determine or put a new limit on the electron neutrino mass. This electroweak production experiment has never been performed previously.

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Physics Motivation

Valuable insights into nucleon and nuclear structure are possible when use is made of flavor degrees of freedom such as strangeness. The study of the electromagnetic production of strangeness using both nucleon and nuclear targets has proven to be a powerful tool to constrain QHD and QCD-inspired models of meson and baryon structure, and elastic and transition form factors [1-5].

By comparison, there are few experimental studies of charged weak transition form factors at intermediate energies [6-10]. With the new high-current, cw electron beam (CEBAF) at Jefferson Lab, it is now feasible to attempt a measurement of the weak production of strangeness to compliment the electromagnetic production data [11].

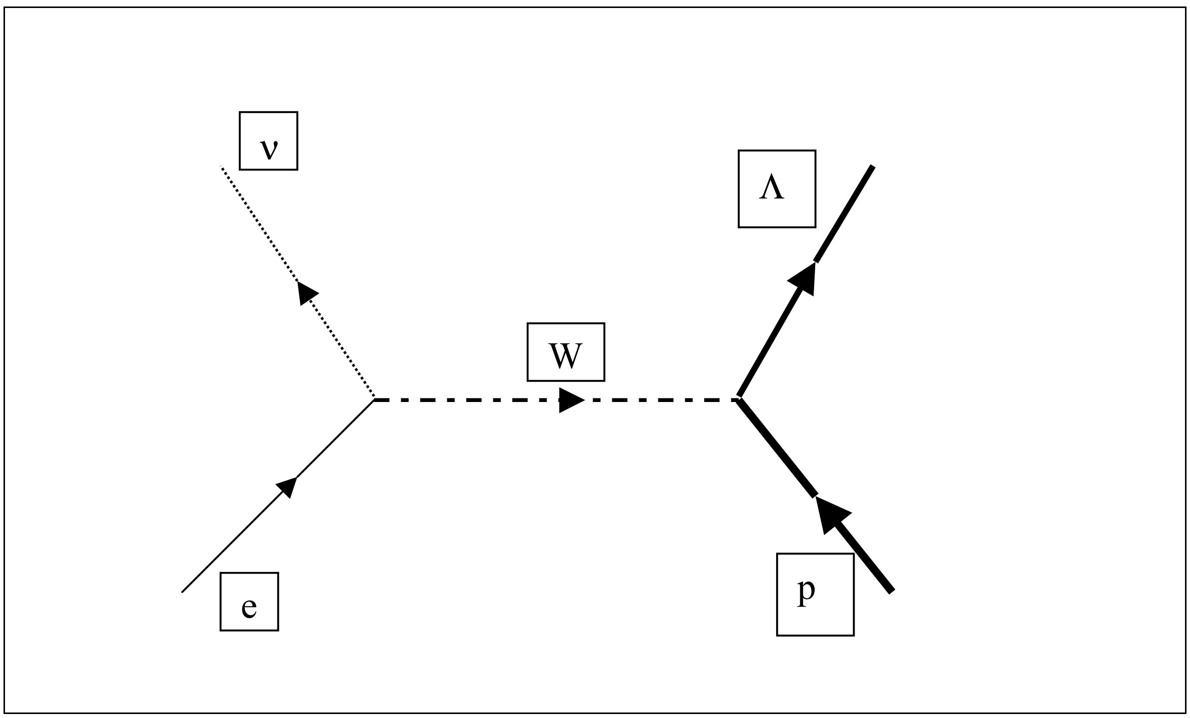


Figure 1. The strangeness-changing electroweak charged-current reaction $\vec{e} + p \rightarrow \nu_e + \Lambda$. The neutrino in the reaction is not detected directly, but through its reconstructed missing mass once the Λ decay products are detected.

In a recent Jefferson Lab Letter of Intent (JLAB LOI 01-107), it was proposed that a precise measurement of the cross section for weak production of strangeness is feasible using the CEBAF cw polarized electron beam [12]. In this present proposal, it is shown that the experiment described in the LOI, with some small modifications, may be used to provide a sensitive probe of non-zero electron-neutrino mass. The experiment would, under a special but certainly compatible configuration, use the helicity dependence of the weak production process as a means of measuring a nonzero neutrino mass. Previous approaches to the question of a massive neutrino involve determination of the endpoint energy in a Curie plot of beta-decays [13-14] and neutrino oscillation searches [15-16]. Recent results from oscillation experiments provide tantalizing evidence for massive neutrinos; only massive neutrinos will convert from one family to another [17]. Oscillation experiments yield information on mass differences between neutrino families. The JLAB experiment may be used to provide a direct measurement of the electron-neutrino mass.

The reaction considered

$$\vec{e} \ + \ p \ \rightarrow \ \vec{\nu}_e \ + \ \Lambda \tag{1}$$

where $\vec{e}$ represents the incident (polarized) electron, p the proton target, ν is the electron neutrino, and Λ is the electroweakly-produced strange hyperon, proceeds via the charged-current weak interaction. The reaction is shown in Fig. 1. The cross section for the reaction has been calculated versus hyperon laboratory angle and incident electron energy for the case of a massless neutrino [18-19]. This weak production process violates parity symmetry maximally. Helicity conservation may therefore be used to identify the reaction at high lepton energies; for massless, or for high energy, neutrinos, only electrons with spin polarization opposite their momentum direction will lead to reaction (1). At high neutrino energies, the empirical evidence supports only neutrinos whose spin direction lie opposite their momentum direction. It has been shown empirically that the left-handed weak charged current interaction mediates this process when the lepton energy is much greater than its rest mass. For massive low-energy neutrinos, this condition is not required.

Helicity Considerations

The helicity of a particle with spin angular momentum $\vec{\sigma}$ moving with momentum $\vec{p}$ is defined as

$$h \ = \ \frac{\vec{\sigma} \ \cdot \ \vec{p}}{|\vec{\sigma}||\vec{p}|}. \tag{2}$$

Massless fermions, moving with speed c have helicity $h \ = \ \pm 1$ always. If the fermions considered are not massless, then their average helicity will fall short of these extreme values. For these massive neutrinos, the average value of the helicity will be $h \ = \ \pm \frac{v}{c}$, even though each measurement will yield the extreme value $|h| \ = \ 1$ for neutrino moving with speed *v*.

So for a fermion with rest mass *m* moving with momentum $\vec{p}$, its velocity may be expressed as

$$\beta \equiv \frac{v}{c} = \left[1 + \left(\frac{mc^2}{pc}\right)^2\right]^{-1/2}. \tag{3}$$

If neutrinos in the weak production process (1) have mass, they move with momenta $|\vec{p}|$ which may be arranged such that $pc \leq mc^2$. In an appropriate experimental arrangement, β can be measurably smaller than one. In the measurement to determine the neutrino mass using the weak process (1), the neutrino velocity does not need to be measured. Only the helicity dependence is used. Positive helicity events resulting from reaction (1) will only occur when the neutrino velocity β is sufficiently small, that is when the neutrino momentum is comparable to or less than the neutrino mass.

Relativistic neutrinos are knows from empirical evidence to be left-handed. So at high energies, only left-handed electrons will produce the result (1). All events recorded in the experiment for right-handed incident electrons will be background events; none from the weak production process. Thus, experimentally it is possible to get a handle on background contamination in this helicity dependence search for neutrino mass. When the kinematics is restricted to high-energy events in (1), only background events will be produced with positive helicity electrons.

Kinematics Considerations

The neutrino and the hyperon in the final state move off in opposite directions (back-to-back) in the center of mass system, both with the same momentum. In the center of mass system, the neutrino moves along a direction with a component, say, the negative-z' direction with speed u' at an angle θ' with respect to the z'-direction. In the lab system, the center of mass itself moves along the z-direction with a speed v. The speed of the neutrino in the lab system is therefore

$$u = \frac{\left[u'^2 + v^2 + 2u'\, v \cos\theta' - \left(\frac{u'\, v \sin\theta'}{c}\right)^2\right]^{1/2}}{1 + \frac{u'\, v \cos\theta'}{c^2}} \tag{4}$$

relativistically. Thus, the experiment may be arranged such that the center of mass is moving along with speed v which equals $-u'$ $(\theta' = 180^0)$. That is, the neutrino speed β (and therefore its momentum) in the lab is zero under these conditions if the neutrino is massive. If the neutrino is massless, the weak reaction only takes place when $\beta = 1$.

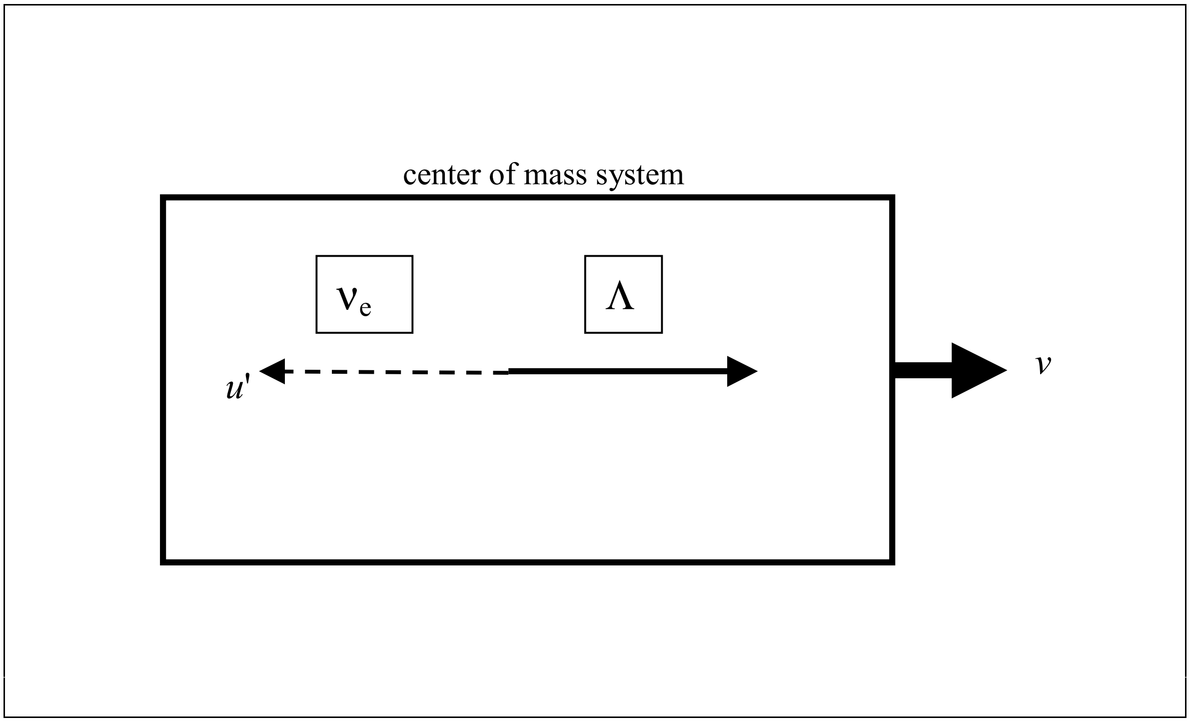


Figure 2. The neutrino and hyperon emerge back-to-back in the center of mass system. The center of mass moves with a speed v in the laboratory system, while the neutrino moves with speed u' in the center of mass system. The reaction may be arranged so that the neutrino speed in the center of mass, u', equals the speed of the center of mass, v. Then the neutrino, if and only if it is massive, will be at rest in the laboratory system.

Recall that it is not the neutrino momentum but rather the neutrino helicity (reconstructed using helicity conservation) that will be used to determine a nonzero neutrino mass. For massless (left-handed) neutrinos, only negative helicity electrons will yield hyperons from the weak process (1). For massive neutrinos, both helicity states will be present for neutrino momenta that are of the order of or less than the neutrino mass.

Experimental Considerations

The Λ hyperon decays approximately 64% of the time into a proton and negative pion as shown in Fig. 3. The decay proton will be detected in the SOS while the negative pion from the decay will be detected in the Enge Split-pole Spectrometer as shown. The proton and pion information will be used to reconstruct the hyperon in the missing mass spectrum. Once the Λ-hyperon is identified in this way, its momentum and energy are determined. Then, using the information on the incident electron and the target proton, the neutrino is identified in a second missing mass calculation; the neutrino is not detected directly. Finally, the use of a polarized electron beam will facilitate the measurement using the neutrino's left-handedness; the electron neutrino will have its polarization vector opposite to the momentum vector for momenta greater than its rest mass. Only one electron helicity direction will produce the reaction shown in Fig. 1 (for a completely polarized beam) in this case.

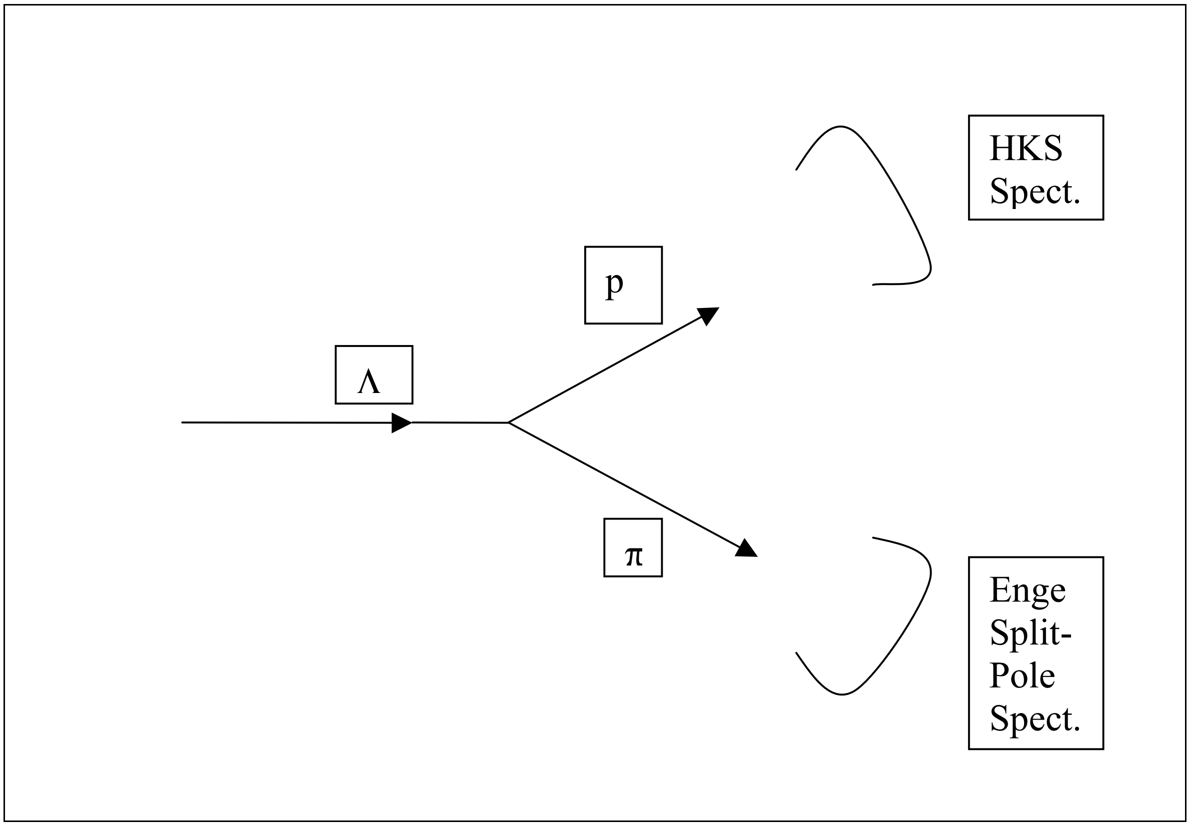


Figure 3. The weak decay of the Λ hyperon. The proton from the decay will be detected in the High-Resolution Hypernuclear Kaon Spectromter (HKS) while the (negative) pion will be detected in the Enge Split-pole Spectrometer. This measurement thus makes use of the existing HKS setup (in the Hypernuclear Spectroscopy Experiment). The ratio of beam energy to pion momentum to proton momentum will be the same as to be used in JLAB Experiment E01-011.

In the experiment, a polarized electron beam of 0.194 GeV and 25 microampers current will be used. It is expected that at this beam current, linearly polarized electrons of up to 80% polarization will be achieved. The experiment will use a solid polyethylene (CH_2) foil for the proton target. CH_2 has a density of approximately 0.94 grams/cc (useful for luminosity calculation). The CH_2 target thickness will be roughly 1 cm. So for an incident electron beam intensity of 25 microampers, the experimental luminosity will be almost 10^{38} $cm^{-2}s^{-1}$. The electroweak production cross sections considered in this proposal can be as high as 10^{-38} cm^2sr^{-1}. <u>For the calculations of the count rate here, we use the conservative value of $6x10^{-39}$ cm^2sr^{-1} to get the estimate of approximately 1000 negative-helicity counts per day.</u> As will be shown later, depending upon the mass of the neutrino, there can be roughly one to a few positive-helicity event (signaling a massive neutrino) per a few hundred negative-helicity event. Details of the experimental setup and procedure are given in section II of this proposal.

Since the neutrino mass is very small compared with momenta usually encountered in low-energy particle physics experiments, a probabilistic approach must be taken in order to measure (or predict) a helicity dependence of the reaction. Experimental velocity resolution, $\delta\beta/\beta$, of approximately 0.025 or better may be achieved in the Jefferson Lab experiments [1,12]. Using (3) it is seen, then, that neutrino momenta of approximately five times or less the neutrino mass will yield helicities that on average differ from one. This proposal takes the conservative approach that the neutrino momentum must be equal to or less than the neutrino mass in order for there to be a positive-helicity event. This forms the basis for the following discussion.

In an experiment with neutrino missing momenta centered on zero momentum in the laboratory frame, a momentum <u>bin</u> of approximately 1 keV/c (for a one-eV/c^2 neutrino mass) is possible. The experiment using the equipment described in [12] will have at best momentum resolution of approximately a few tens of keV/c. (The momentum resolution in the experiment will be roughly 50 keV/c or less as shown in Table I. However, the resolution of each momentum <u>bin</u> will be roughly 0.02 of that value.) Thus, the probability that an experiment with the reconstructed neutrino momentum resolution centered on zero will be 1 eV/c or less is approximately one in a few hundred. One in a few hundred events will be from right-handed electron scattering to produce reaction (1) for neutrinos of roughly 1 eV/c^2 mass. This is shown pictorially in Figure 4.

Table I: The energy resolution of the experiment will be approximately 50 keV with the contributions from the sources shown. Then, for a high resolution ADC and/or TDC, this 50 keV will be distributed evenly over approximately 50 bins. Then the bin resolution will be approximately 1 keV. The importance of this result is shown in Figure 4.

source of uncertainty	**Value**	**Contribution**
incident beam energy	$1x10^{-4}$	20 keV
proton momentum measurement (in HKS)	$2x10^{-4}$	20 keV
pion momentum measurement (in Enge)	$4x10^{-4}$	40 keV
Misc (target, electronics, etc)		10 keV
Total uncertainty (energy resolution)		**~50 keV**

It is essential, then to design a high-resolution experiment with high statistics for an unambiguous measurement. The experiment must be in a kinematics region where the cross section is large and where the neutrino laboratory momentum is small (less than its rest mass). These requirements are compatible at threshold for the weak production process as now shown.

Cross Section for Weak Production of Strangeness at Threshold

The differential cross section for the reaction (1) may be written as [11,18-19]

$$\frac{d\sigma}{d\Omega} = \frac{m_e m_\nu G^2 m_f p_f |M|^2}{(2\pi)^2 E8 \left| m_i + E - EE_f \cos\theta / p_f \right|} \quad (5)$$

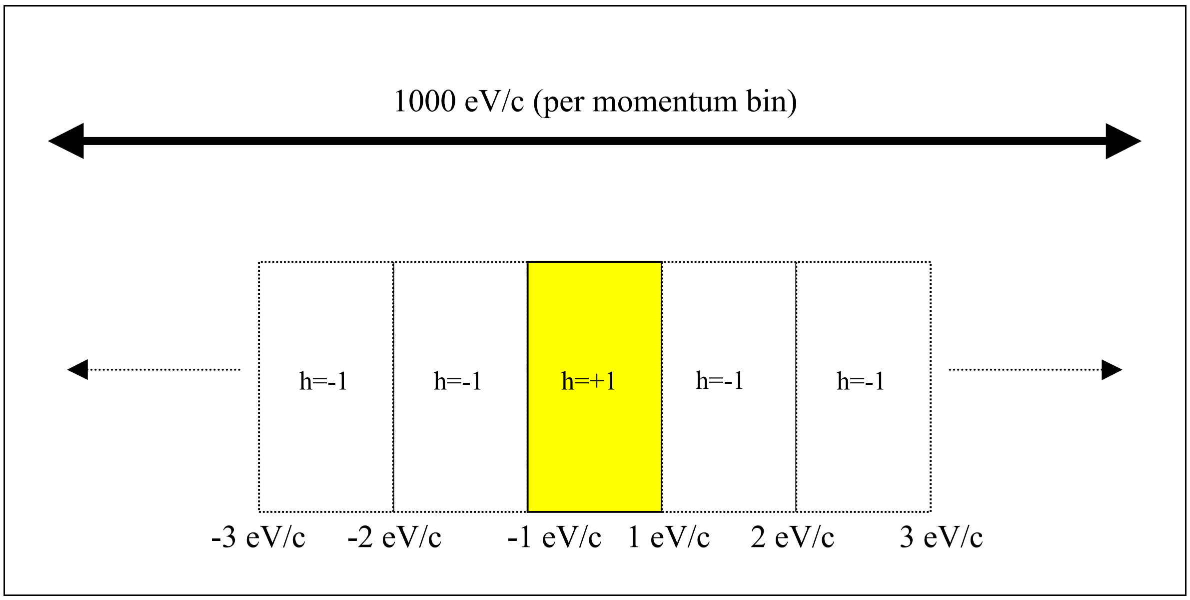


Figure 4. The missing momentum is shown along the horizontal axis while the helicity is shown vertically. A positive helicity weak production event will occur only if the neutrino momentum is within plus or minus 1-2 eV/c of zero (for a neutrino of one eV/c^2 mass) out of a total of one keV/c or so bin resolution. Thus approximately one in a few hundred or more weak production events will result from a positive helicity incident electron in a single momentum bin. There will be several tens of these bins. In a high statistics experiment such as the one planned, it should be feasible to get unambiguous evidence for massive neutrinos in a few weeks of running.

where m_e and m_ν are the electron and neutrino masses, G is the Fermi coupling constant, m_f denotes the final state hyperon with momentum p_f and energy E_f. E is the incident electron energy, m_i is the proton mass, and θ is the angle between the incident electron and the outgoing Λ-hyperon. M is the electroweak matrix element expressed in terms of the weak form factors via the vector and axial-vector weak couplings:

$$M \sim \left\langle \Lambda \middle| V_\mu^{!}(0) \middle| p \right\rangle - \left\langle \Lambda \middle| A_\mu^{!}(0) \middle| p \right\rangle \tag{6}$$

$$\left\langle \Lambda \middle| V_\mu^{!}(0) \middle| p \right\rangle = \bar{u}_f \left[\chi_\mu F_v(q^2) + i \frac{F_M(q^2)\sigma_{\mu\nu}q^\nu}{2m_p} - F_S(q^2) \frac{q_\mu}{2m_p} \right] u_i \tag{7}$$

$$\left\langle \Lambda \middle| A_\mu^{!}(0) \middle| p \right\rangle = \bar{u}_f \left[\chi_\mu \chi_5 F_A(q^2) + i \frac{q_\mu \chi_5 F_P(q^2)}{2m_\pi} + \frac{iF_E(q2)\sigma_{\mu\nu}q^\nu \chi_5}{2m_p} \right] u_i \tag{8}$$

Following the work of [18] and [19], we calculate the cross section of weak production of strangeness;

$$\frac{d\sigma}{d\Omega} = \frac{m_e m_\nu G^2 m_\Lambda p_\Lambda |M|^2}{(2\pi)^2 E8 \left| m_p + E_e - E_e E_\Lambda \cos\vartheta / p_\Lambda \right|} \tag{9}$$

where E_e is the incident electron energy, $E_\Lambda(p_\Lambda)$ is the hyperon total energy (momentum), m_Λ is the hyperon mass, and ϑ is the angle between the incident electron and the hyperon. $|M|$ is the matrix element for the reaction. Each term in the expression for $|M|^2$ is proportional to the neutrino energy times the appropriate hadronic form factors; vector, axial vector, magnetic, and electric. The axial vector form factor is dominant at the kinematics of interest here [18-19] and are the only ones considered in the following analysis. The simplified expression for the matrix element may then be written as [18-20]

$$|M|^2 \approx \frac{4|F_A|^2}{m_e m_\nu m_p m_\Lambda} \left[p_\Lambda \cdot \nu p_p \cdot e + p_\Lambda \cdot e p_p \cdot \nu + e \cdot \nu m_p m_\Lambda \right] \tag{10}$$

The cross section may be made arbitrarily large by choosing the kinematics such that $\beta_\Lambda = \frac{p_\Lambda}{E_\Lambda} = \left(1 + \frac{m_p}{E_e}\right)^{-1}$; that is where the denominator in (5) vanishes. Additionally, for the purposes of determining the neutrino mass, the kinematics must be chosen such that β_Λ yields a close to zero-momentum neutrino in the laboratory frame. These two requirements are compatible at the threshold for the weak production reaction. With an incident electron beam, the threshold energy for reaction (1) is 0.1940 GeV/c^2. The higher the momentum resolution of the experiment, the higher will be the cross section for the reaction at threshold.

The cross section versus hyperon momentum is shown in Figure 5. The cross section peaks at the value of β_Λ described above. The peak is wide enough that it can be readily discerned in a Jefferson Lab experiment as described in [1]. For the experimental resolution attainable using the CEBAF beam and the associated equipment, the cross section is seen to increase by an order of magnitude over that farther away from this "magic" kinematics. With the luminosity and solid angle planned for the experiment, one may expect close to 1000 weak production counts per day corresponding to reaction (1). With momentum resolution of order 50 keV/c in the hyperon (or neutrino) missing mass reconstruction, and the results of the discussion above, it is reasonable to expect unambiguous evidence for neutrino mass in this experiment. For a momentum resolution of approximately 50 keV/c, a single channel in the missing mass spectrum will represent approximately 1 keV/c^2 (or close to 1 keV/c^2) for high resolution electronics (TDC's/ADC's). The probability of a positive helicity neutrino event in that 1000 eV/c^2 channel will be approximately 1/400 or close to 1/(a few hundred) if the neutrino mass is around 1.0 eV/c^2. Table II below shows the number of counts expected for the same 1000 eV/channel resolution for several values of the neutrino mass.

Table II: The mass of the electron-neutrino determines the probability for a positive helicity (h+) event (above background) given a fixed experimental resolution of approximately 1.0 keV/c in a single momentum bin. In a 10-day run, there should be sufficient positive-helicity counts (10 or more) above background to signal unambiguous evidence for electron neutrino mass. The result is given in terms of the ratio of positive helicity events (h+) to negative helicity (h-) events.

Neutrino mass (eV/c^2)	*h+/h-* counts above background
1.5	1/200
1.0	1/400
0.5	1/800
0.25	1/2000

Using equation (3) it is possible to estimate the number of positive-helicity events due to the weak production reaction (1). These events will have a statistical distribution according to the mass of the electron-neutrino. The larger neutrino momenta (with respect to the neutrino mass), the smaller the probability for an event of interest. Table III shows the probability for a positive-helicity event for a given neutrino momentum if the neutrino mass is 0.5 eV/c^2. For larger neutrino mass, the corresponding probabilities will be higher.

Table III: The probability for a positive-helicity event will depend upon the velocity of the neutrino produced in the reaction. The lower the momentum, the higher the probability as indicated. Shown here are the values for a neutrino mass of 0.5 eV/c^2

pc/mc^2	β	Probability ("+" helicity)
0.0	0.00	1.00
0.2	0.20	0.80
0.5	0.45	0.55
1.0	0.71	0.29

To summarize, it has been shown that a sensitive measurement of the electron neutrino mass may be made using the weak production of strangeness process. The measurement will make use of the helicity dependence of the reaction using polarized electrons incident upon a proton target. The reaction will take place at the threshold for the process where the neutrino velocity in the laboratory frame is zero and where the cross section for the reaction is maximized.

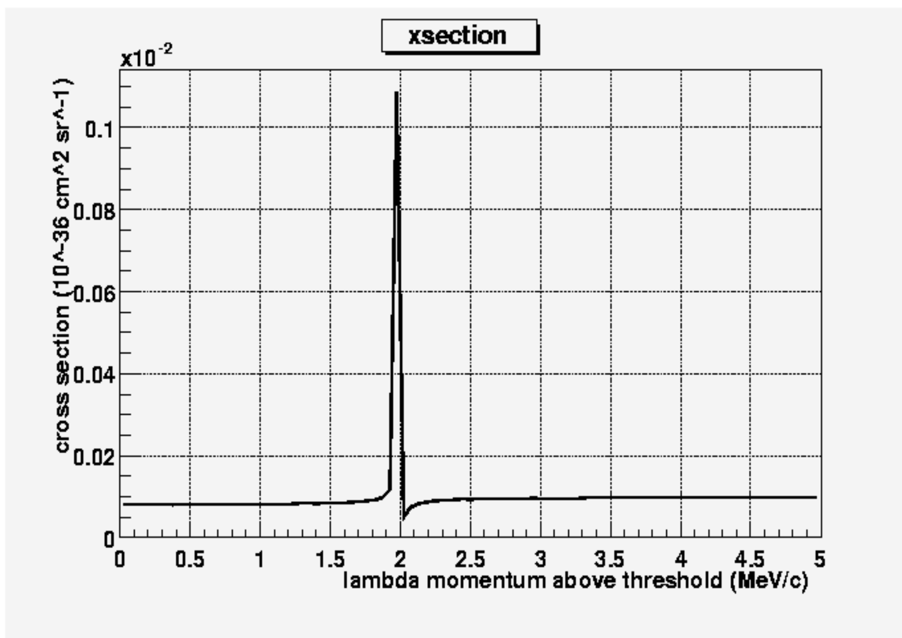


Figure 5. The weak production of strangeness cross section versus the hyperon momentum (relative to threshold). The cross section is maximum at the same value that the neutrino momentum is zero in the laboratory frame under the chosen set of kinematics.

Other Physics

Determination of weak nuclear form factors

Shown in Fig. 6 is the differential cross section for the reaction (1) versus Λ laboratory angle for several different incident electron energies. The cross section peaks rather sharply at a hyperon lab angle of about 40^{o} for an incident energy of 1 GeV; the cross section is approximately 10^{-39} cm^2/sr there. The experimental proposal here would use an incident electron energy of 194.0 MeV. However it will still be possible to get the information about the axial-vector form factor as with a higher incident beam energy.

The contribution of the various form factors to the differential cross section is shown in Fig. 7 as a function of the outgoing Λ laboratory angle for an incident electron energy of 4.0 GeV. The dominant contribution comes from the axial-vector form factor F_A over most of the angles, although they all peak at about 50° for this energy. The calculations for a 0.194 GeV incident beam are being made presently.

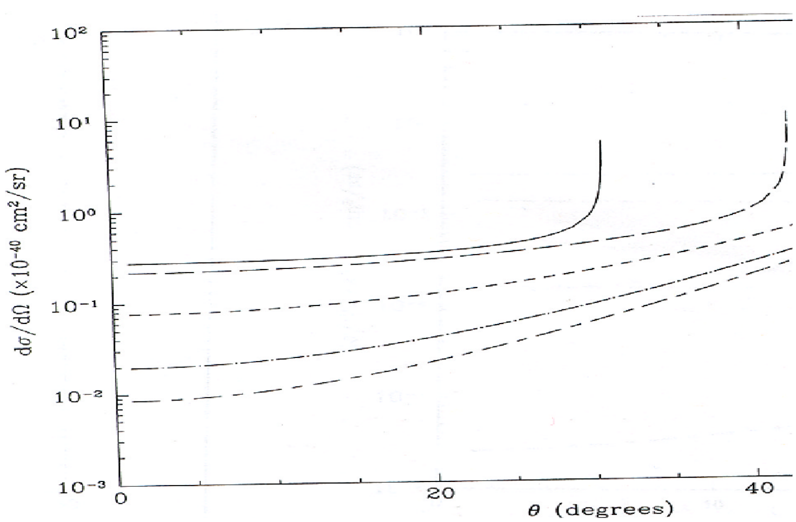


Figure 6. The laboratory differential cross section for weak production of Λ-hyperons versus the angle that the hyperon makes with the incident beam direction. The cross section is shown for several different incident electron energies from 0.5 to 6.0 GeV. The figure is taken from [18].

Stellar dynamics

The weak process described in this LOI is of major importance in stellar dynamics and supernovae explosions [21]. Weak production of nucleons and hyperons are believed to be a means of removal of internal energy from an expanding shock wave in core collapse during supernovae formation [21]. There are predictions that strange stars, that is stars that have significant s-quark or hyperon dynamics, are more abundant in our universe than neutron stars. The process

$$u + d \leftrightarrow s + u \tag{11}$$

is believed to be the dominant one sustaining these predicted strange stars. The reaction involving the up and strange quark will be studied in the JLAB experiment.

Relation to Drell-Yan-like process to be studied at the Large Hadron Collider

The reaction shown in Fig. 1 is related to the Drell-Yan-like production of W bosons that will be studied at the Large Hadron Collider (LHC). At the LHC, the proton-proton

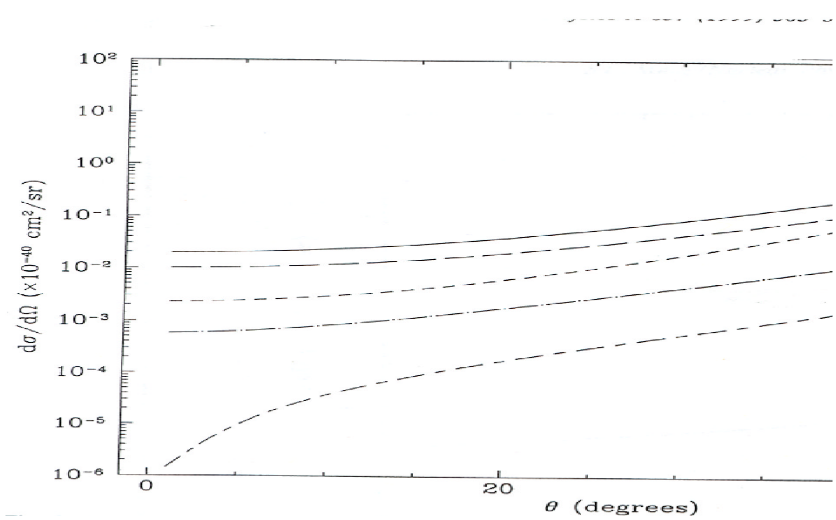


Figure 7. The contributions from several form factors that contribute to the weak production process versus the angle that the Λ-hyperon makes with the incident beam direction. All of the form factors peak at about 50 degrees for this incident electron energy (4.0 GeV). The figure is taken from [18].

collisions at 14 TeV center of mass energy may be viewed as the scattering of the hadron's constituents. Precision electroweak measurements form one of the most compelling reasons for the construction of the LHC and its detectors. The lowest-order diagram describing the LHC process of interest in this LOI is shown in Fig. 8.

This mechanism of producing W bosons represents one of the cleanest processes with a large cross section at the LHC [22]. The LHC reaction is well suited for a precision measurement of the W boson mass, and it is expected to yield valuable information on the parton structure of the proton. The lowest-order differential cross section for the reaction of Fig. 8 can be related to the CKM matrix element $V_{qq'}$. The JLAB experiment shown in Fig. 1 can, in principle, provide complimentary information about this electroweak process and therefore information on the CKM matrix element as well.

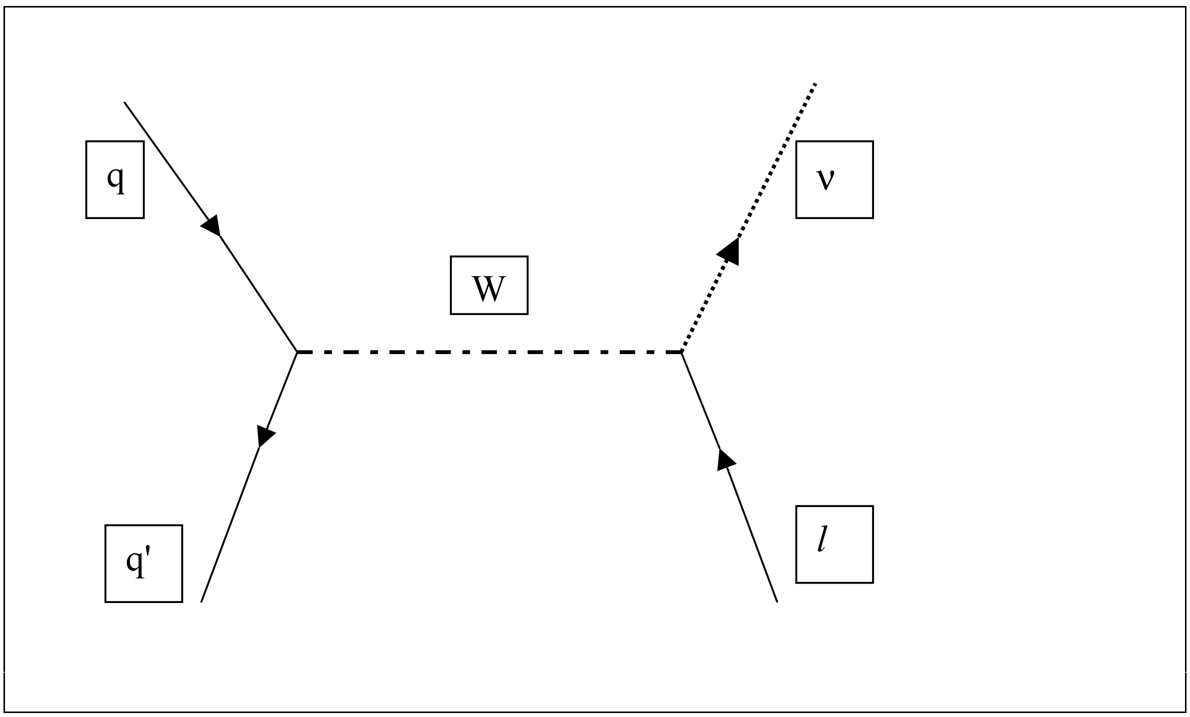


Figure 8. The lowest order Drell-Yan-like diagram for W boson production at the LHC. This process is similar to the reaction to be studied in the JLAB experiment described in this proposal (see Fig. 1).

Experimental Procedure

The experiment will be studied in Hall C using the High Resolution Kaon Spectrometer (HKS) and the Enge Split-pole Spectrometer. The HKS will be used to detect and identify the protons in a modest background of positive pions and a small background of kaons. The collaboration has had extensive experience using the Hall C SOS and Enge to detect electron-kaon coincidences in the past. The detector stack to be used in the HKS is practically identical to the one that was used in the SOS. The detector stack to be used is shown in Fig. 9 below.

It is important to note that the ratio of incident electron beam energy to HKS momentum setting and to Enge Split-pole spectrometer setting will be the same as in JLAB Experiment E01-011. So there will be no need to change the experimental configuration from that of the hypernuclear experiment. The details of the E01-011 experiment describing the spectrometers and their performance are presented elsewhere [23] will not be repeated here. The experiment described in this proposal is completely compatible with E0-011 already approved and having passed a Technical Design Review at Jefferson Lab.

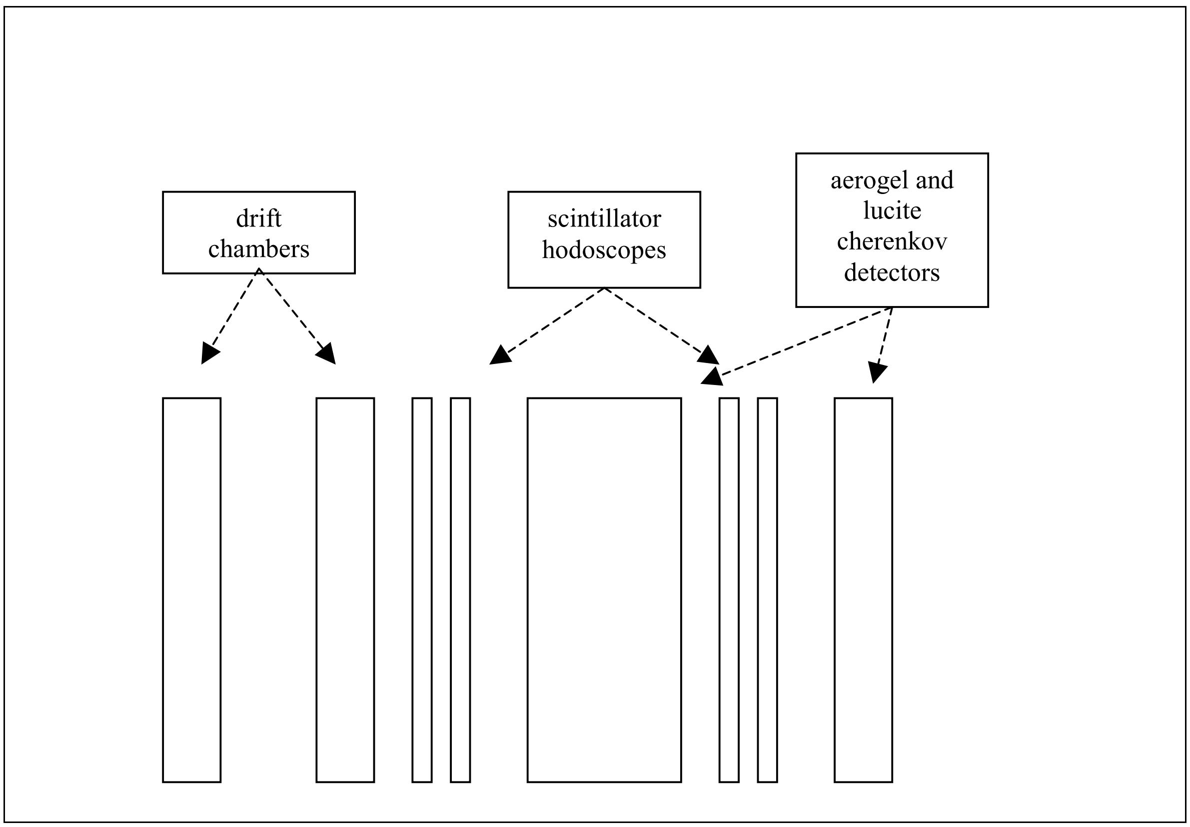


Figure 9. The proposed detector stack for the HKS spectrometer (the hadron arm). This is the same detector stack that was used in the HNSS experiment E89-009 at JLAB. The particles to be detected are incident from the left.

The HKS will have two sets of planar drift chambers for particle trajectory reconstruction. There will be six planes per chamber (XYUVY'X'). The wire chambers used in conjunction with the spectrometer magnets is expected to yield a momentum reconstruction accuracy, $\delta p/p$, of better than or equal to $2x10^{-4}$. There will be two sets of scintillator hodoscopes for triggering and fast timing. Each set will contain X and Y hodoscope planes. Previous experience with the SOS scintillator hodoscopes has shown that it is not unreasonable to expect timing resolutions per plane, δt, of better than 300 ps. For particle identification (pid) the HKS will make use of two types of Cherenkov detectors, a silica aerogel-based diffusion box detector and a total internal reflection lucite counter. A similar system used in the SOS during the HNSS experiment (JLAB Experiment E89-009) achieved pion/kaon separations of better than 300/1 and proton/kaon separation of better than 200/1. These will be more than adequate for the present study.

The Enge Split-pole Spectrometer will be used to detect and identify negative pions in a background of electrons and muons, mainly. The spectrometer is the same that was used in E89-009, but now with a proposed new detector stack shown in Figure 10.

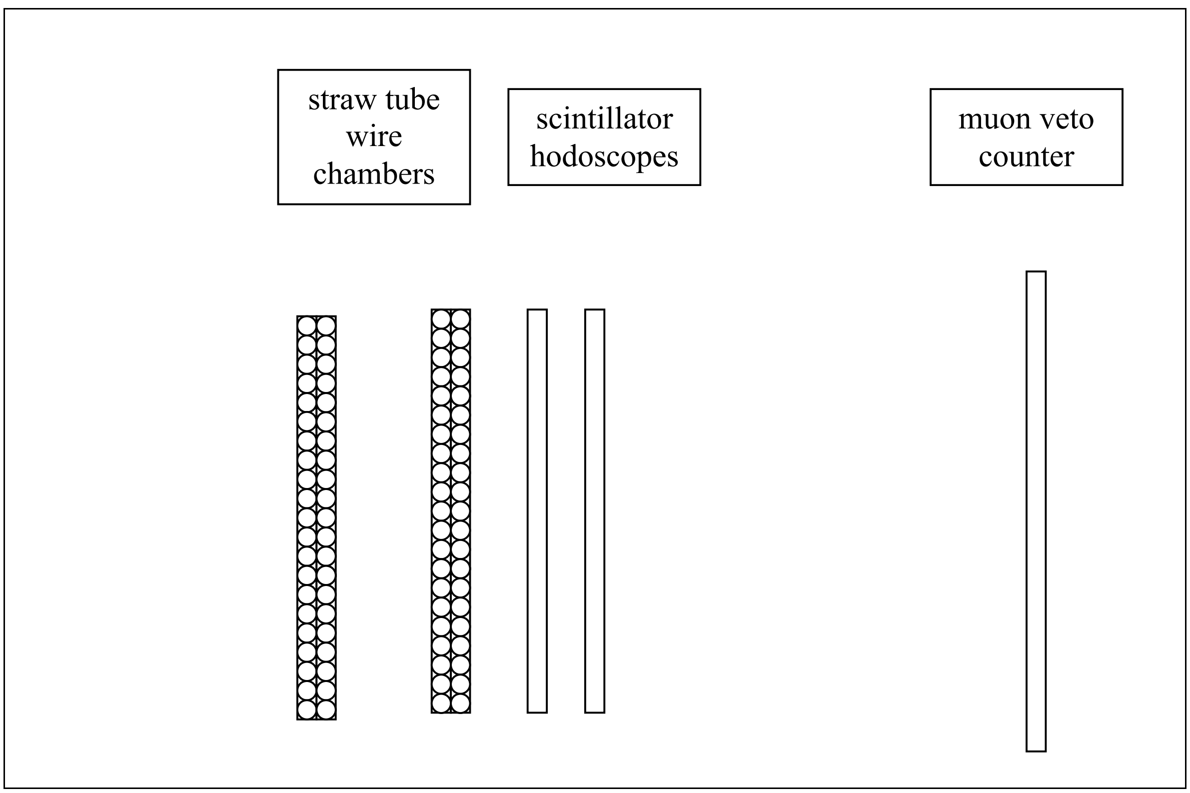


Figure 10. The proposed detector stack for the Enge Split-pole Spectrometer (the negative hadron arm). This is the same spectrometer that was used in JLAB experiment E89-009, only with a new detector arrangement. The particles to be detected are incident from the left.

There is a strong correlation between the angle and momenta of the emergent proton and pion coming from the hyperon decay. For fixed spectrometer angles (and acceptances) the decay particles' momenta are specified for the reaction under study. Simulations have been done for an incident electron momentum of 194.0 MeV, and zero degree settings (with respect to the incident electron beam) for both spectrometers. The HKS and Enge spectrometers will have an angular range large enough to detect protons of up to four degrees and pions up to 0.5 degrees, respectively, with respect to the incident electron beam. Thus the angle between the proton and pion from the hyperon decay will be about seven degrees (in the laboratory frame). The proton momentum will be approximately 0. 069 GeV/c while the pion momentum will be approximately 0.130 GeV/c in order to detect the reaction given in (1). Again, it is emphasized that the ratio of energies and momenta are the same as in E01-011 already approved for running.

Previous experience with Jefferson Lab experiments E91-016, E93-018, and E89-009 (all kaon electroproduction experiments) indicate that the coincidence spectrum for the HKS will be that shown in Fig. 11. Displayed in this figure along the vertical axis is the velocity of the positive hadron detected (with respect to the speed of light) versus the coincidence time along the horizontal axis. There are three different particle types detected; positive pions (β~1), kaons (β~0.9), and protons (β~ 0.8).

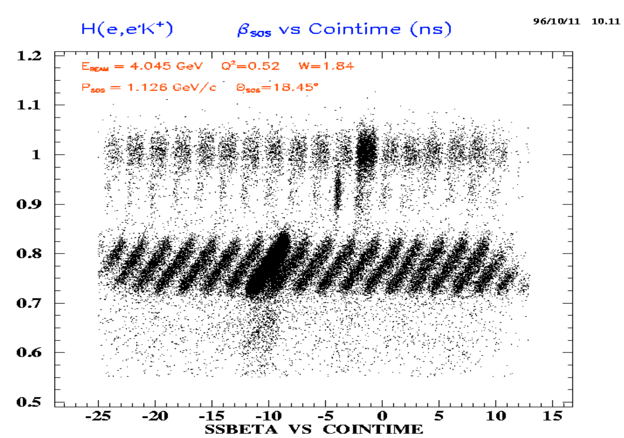


Figure 11. The coincidence spectrum from Experiment E93-018 and E89-009 at the positive hadron arm spectrometer momentum setting appropriate for studying reaction (1). There are three different types of positive hadrons clearly identified - pions, kaons, and protons. This spectrum is similar to the one expected for the HKS in the coincidence experiment except that the momenta (and therefore β) will be smaller (70 Mev/c) and there will be no kaons present; this experiment is below the threshold for electromagnetic production.

The hodoscope timing will be sufficiently accurate to separate the rf structure of the CEBAF beam. A representative spectrum taken from the Enge Split-pole Spectrometer of E89-009 is shown in Fig 12. This same rf structure is seen along the horizontal axis of Fig. 11. The missing mass spectrum shown in Fig. 13 is generated from the information shown in Figs. 11 and 12. In this case, taken again from Experiment E89-009, a cut was made of the kaons from Fig. 11, and the appropriate rf bucket for electrons from Fig. 12.

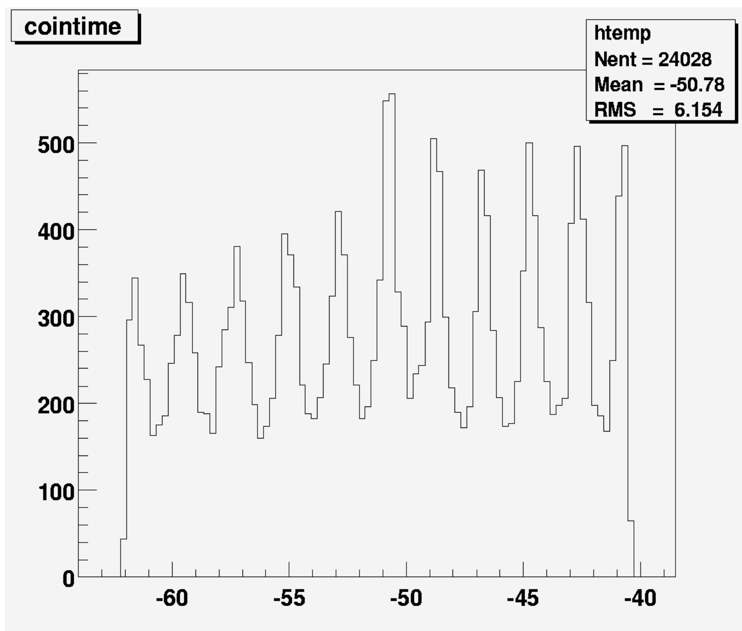


Figure 12. The rf structure of the CEBAF beam. Timing relative to these beam bursts are used for particle identification.

The peaks corresponding to the Λ and Σ^o hyperons are clearly seen in the missing mass spectrum of Fig. 13. These hyperons coming from the hydrogen in the CH_2 target clearly stand out on top of the broad distribution of random coincidence events and contributions from the carbon scattering.

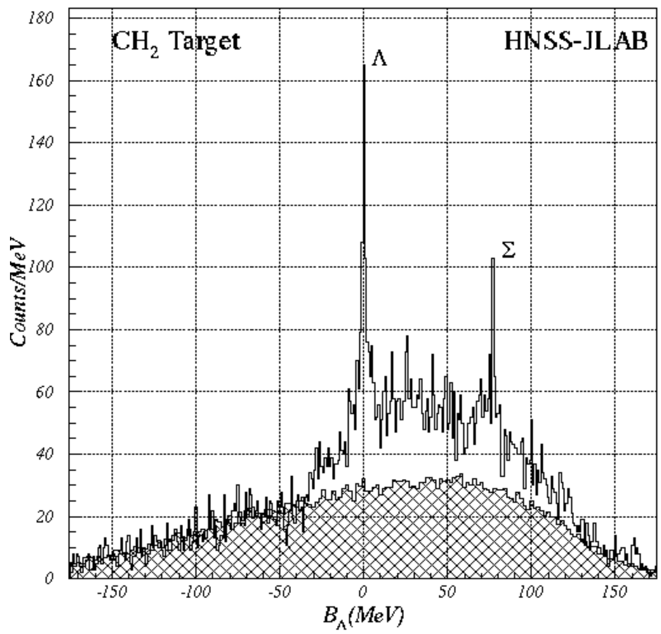


Figure 13. The missing mass spectrum calculated from the kaons detected in the SOS and the electrons detected in the Enge Split-pole Spectrometer from experiment E89-009. The Λ and Σ^o hyperons from the reaction on the hydrogen in the CH_2 target are clearly identified on top of accidental coincidences, and the background events coming from scattering from carbon. It is expected that the Λ hyperon peak from reactions (1) can be cleanly identified in a similar manner in the proposed experiment.

In Fig. 13, accidental background contributions (including some pion contamination) to the spectrum has been estimated by using eight accidental coincidence time windows surrounding the real coincidence peak and subtracted. The effect of beam energy drift is found to be negligible.

Separating out the carbon contribution to the scattering is expected to be straightforward, based upon prior experience in E89-009. A long carbon run yields the spectrum shown in Fig. 14. The distributions is fitted quite easily as shown. The subtraction of the carbon contribution from the CH_2 target will be done bin-by-bin. For the spectrum shown in Fig. 14, the background includes accidentals and real coincident pions leaking through the cut on particle velocity (β). The accidental coincidence peaks were used for accidentals' analysis.

The percentage of real coincident pion leaking through was analyzed using fits in the beta cut for both real and accidental coincidences. The difference gave the real pion leakthrough; accidental pions are naturally included in the accidental background. The pion selection with (e,e'K^+) kinematics gives the histogram shape. The background was fitted by a fourth order polynomials with confidence level of 100%. The Chi-square per number of degrees of freedom, confidence level, and the actual function are shown in the figure.

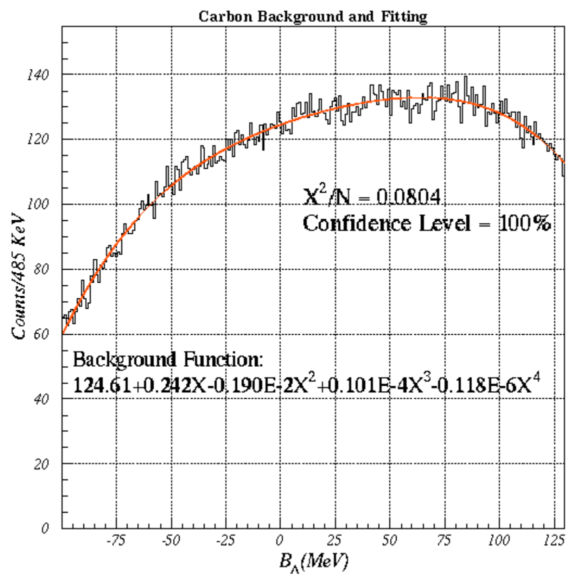


Figure 14. The analysis of the background coming from scattering on carbon in the CH_2 spectrum.

The experiment proposed in this document will use a CH2 target of approximately 1 cm in thickness. The target will be cooled by placing it on a Be backing as shown in Fig. 15. The heat dissipation achieved with this setup will be adequate to handle a 50 μA beam-on-target.

Simulations using the SOS and Enge Split-pole Spectrometer setup in Experiment E89-009 indicates that the measurment proposed here is feasible. Using the energy and momenta of the pion and proton (from the hyperon decay) allows a reconstruction of the missing mass. This simulation, shown in Fig. 16, indicates that the Λ peak at 1.115 GeV will stand out above the background sufficiently to identify it. The simulation using realistic production from a CH_2 target, with real and random pion-proton coincidences. The HNSS system achieved an energy resolution of better than 800 keV in the missing mass spectrum shown in Fig. 13. This is useful in the proposed experiment. The peak should sit in a very narrow region of the spectrum compared with the backgrounds that are spread out over the entire spectrum as shown in Fig. 16. The current experiment expects an energy resolution of better than 50 keV.

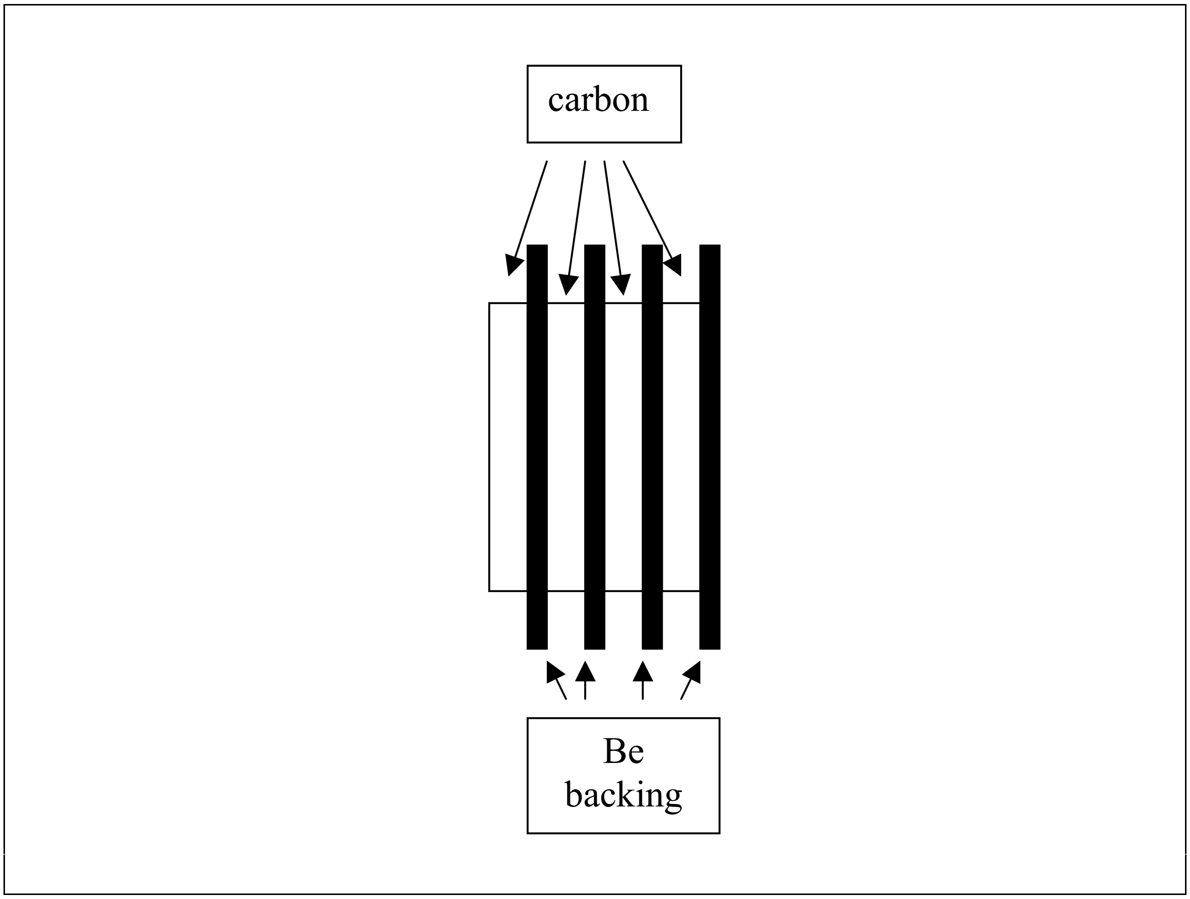


Figure 15. The proposed CH_2 target for the proposed experiment. The CH_2 foils will be mounted on a Be backing which will provide stability and a path for cooling. The Be will contribute a negligible amount to the coincidence spectrum.

For the simulated spectrum shown in Fig. 16, the SOS was set to a central momentum appropriate for this experiment (the SOS has a +/- 20% momentum bite). This allows the protons of roughly 0.070 GeV/c to be easily detected with a cut on particle velocity. This is shown in Fig. 11 where the SOS was at approximately this momentum setting. The Enge Split-pole Spectrometer which will detect the pion has a large momentum bite as shown in Fig. 14. The Enge Split-pole Spectrometer was used to detect the electrons during experiment E89-009 (HNSS Experiment). A good calibration of the spectrometer was obtained for the detection of electrons in the (e,e'K) reaction with the hyperon missing mass calculated as shown in Fig. 13.

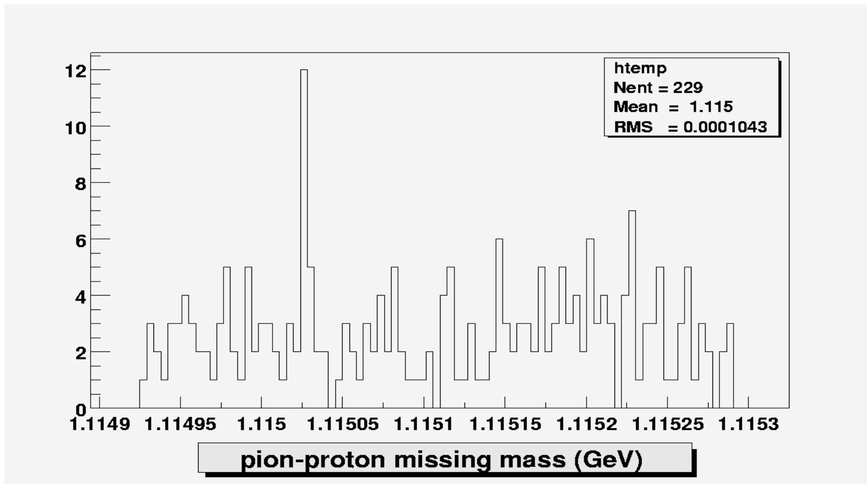


Figure 16. The missing mass spectrum calculated from the detected pion and proton resulting from the hyperon decay. The peak at 1.115 GeV stands out well enough above background to be clearly identified. This spectrum represents what may be expected in a single hour of running.

The weak production experiment proposed here will use straw-tube wire chambers as opposed to silicon strip detectors which were used in the HNSS experiment. Thus, some information on the angle that the detected charged particles make (with respect to a central axis through the detector stack) will be gathered. It is expected that some calibration data using the (e,e'K) reaction on hydrogen will be gathered before this experiment runs. The calibration should be good for the experiment proposed here.

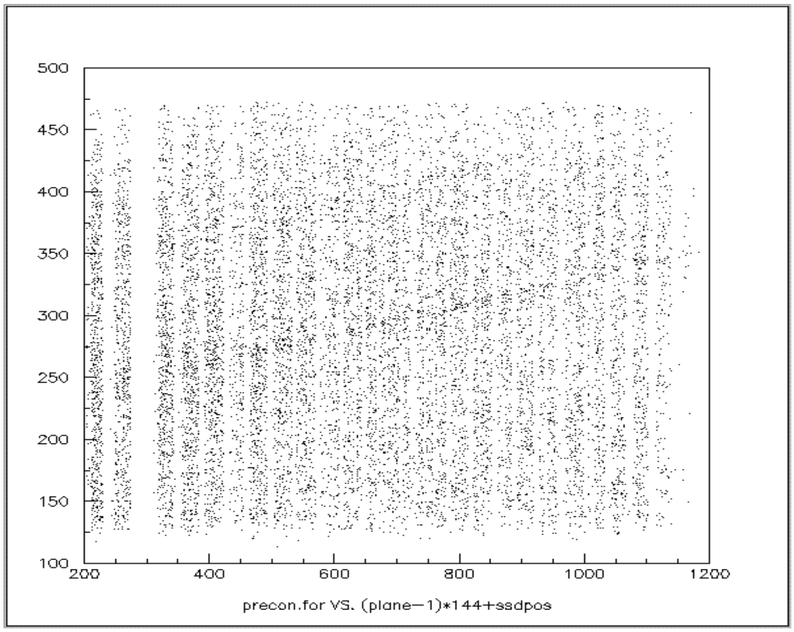
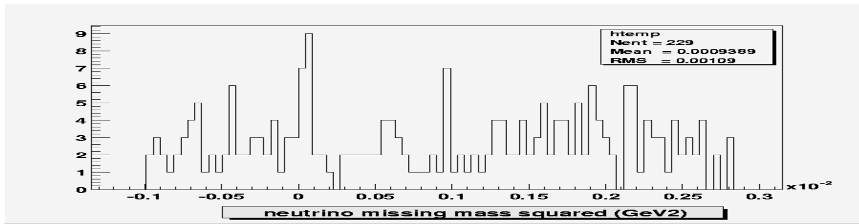


Figure 17. The momentum of the Enge Split-pole Spectrometer is shown along the vertical axis versus the Silicon Strip Detector channel along the horizontal axis. This calibration was taken during the HNSS Experiment E89-009. The dark band in the center of the spectrum is the reconstructed Λ hyperon from the p(e,e'K)Λ reaction on a CH_2 target. The central momentum setting in the Enge Split-pole Spectrometer will be lowered to roughly 130 MeV/c central momentum setting as opposed to the 300 MeV/c setting shown here.

Once the hyperon missing mass is reconstructed, the reaction shown in Fig. 18 is identified. Then the information from the incident electron beam and target proton may be used to reconstruct the neutrino missing mass. This was simulated, again using a realistic CH_2 target along with real and random coincidences. An unpolarized electron beam of 194.0 MeV was incident upon the target. Then using equation (1) the spectrum shown in Fig. 18 was obtained. Note that the neutrino peak stands out above background for the same left-handed may reduce the background even further. Fig. 18 uses the information from Fig. 16 (same calculations and cuts applied). Again, this represents about one hour of running for the experiment conditions in the proposed weak production experiment.



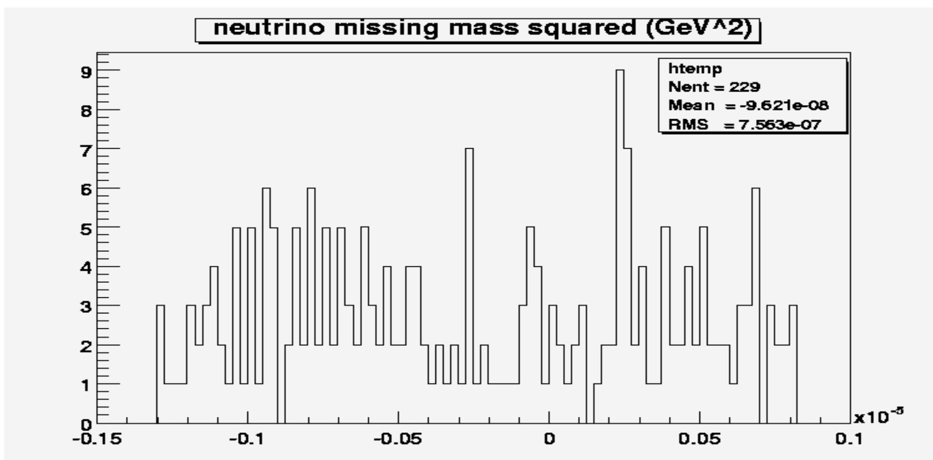


Figure 18. The missing mass squared from the reaction given in (1). This uses the information from the spectrum of Fig. 16. The neutrino peak stands out above background well enough to be identified. It is expected that the use of a polarized electron beam will be useful in reducing the background even further as explained in the text. This spectrum represents about one hour of running for the proposed weak production experiment.

Backgrounds, Rates, and Beam Time Request

Background processes

The following background processes were considered and shown to be manageable in this experiment.

$$e + p \rightarrow e' + K^{+} + \Lambda \qquad \text{(electromagnetic production)} \qquad (12)$$

The experiment will use an incident electron beam of 0.194 GeV which is below the threshold for electromagnetic production of strangeness. Thus this reaction does not contribute to the background.

$$e + p \rightarrow e' + p \qquad \text{(e misidentified as a } \pi\text{)} \qquad (13)$$

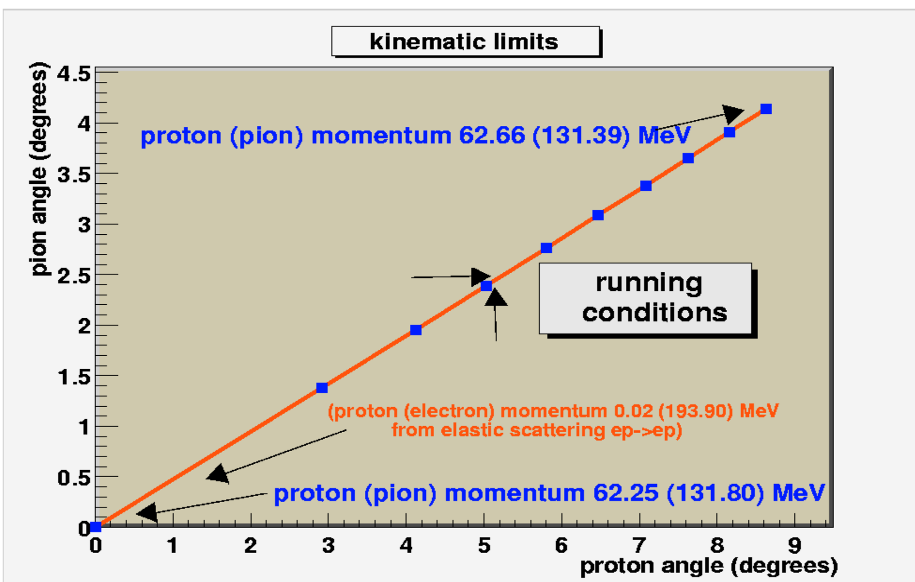


Figure 19. The kinematic limits on the reaction of interest compared with the that from elastic scattering where the electron is misidentified as a negative pion. The two reactions occupy different regions of phase space. It is not possible kinematically for the electron and pion from the background process to have the same momenta as the proton and pion from reaction (1).

In this case, the elastic cross section is very large compared with the weak production of strangeness. Then if only a few scattered electrons are misidentified as pions, this would be a major source of background. However, the elastic reaction (13) occupies a different region of phase space from reaction (1) in this experiment (see Fig. 19). It is impossible to get the energy (momentum) of both scattered electron and scattered proton high enough to mimic the pion and proton from hyperon decay. Thus elastic scattering of electrons by protons with particle misidentification does not pose a background.

$$e + p \rightarrow e' + \pi^+ + n \qquad \text{(e misidentified as a } \pi^- \text{; } \pi^+ \text{ misidentified as a p)} \qquad (14)$$

The electromagnetic production of pions from a proton target where the electron is misidentified as a negative pion and the positive pion is misidentified as a proton with a neutron in the final state. In the missing mass spectrum that is generated in the experiment, the neutron and Λ-hyperon are well separated in energy so that misidentification of these baryons poses no problem. The electromagnetic production of pions (14) will not contribute to the background. It is also important to note that the production of reaction (1) off of the carbon target is very low compared with that from the proton. Shown in Fig. 20 is the result of running the same algorithm as produced Figs. 18 and 19, but on the carbon target (for the same statistics). There is virtually no background contribution from carbon.

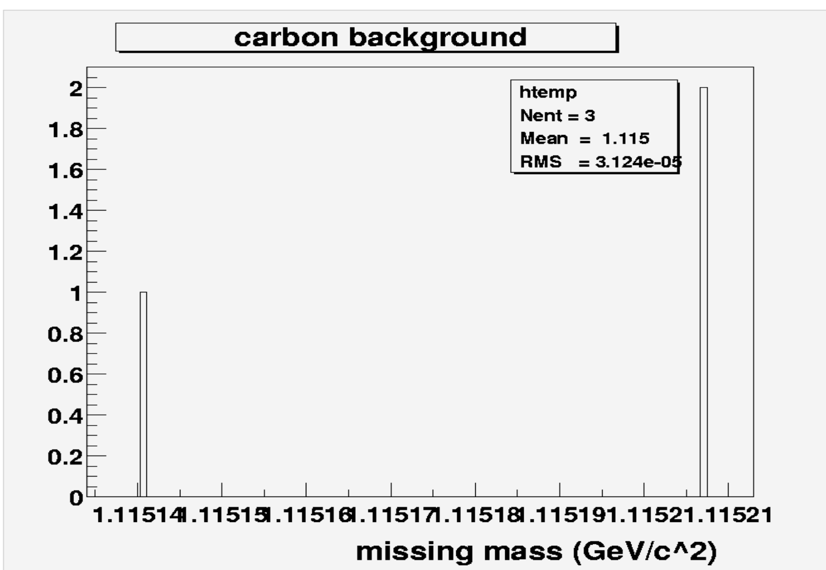


Figure 20. The contribution from the carbon target for reaction (1) obtained using the same algorithm that generated Figs. 17 and 18 and for equal running times. It is seen that there is very little contribution from the carbon target for the reaction of interest.

$$e + p \rightarrow \nu_e + \Delta^0 \qquad \text{(weak } \Delta \text{ production)} \qquad (15)$$

The cross section for weak production of the delta baryon is approximately twice as high as that for strangeness production. Even though the experiment will use an incident beam of energy below the threshold for production of the Δ(1232) for central mass values, the Δ is very broad in mass and its tails could contribute to the missing mass spectrum in the calculation described above. However, the Λ-hyperon, with mass of 1.115 GeV/c^2 will be a delta function peak in the missing mass spectrum (compared to the Δ-baryon), and well separated from the Δ(1232) so that contributions from the reaction (15) will not pose any significant background.

$$e + n \rightarrow e' + \pi^- + p \text{ (electromagnetic production from carbon)} \qquad (16)$$

Since the target will be CH_2, there is the possibility to produce a proton and negative pion from the neutron in the target. Because this is an electromagnetic process, the displaced vertex from the target can be used to eliminate this background; the hyperons will decay outside of the 1-cm target.

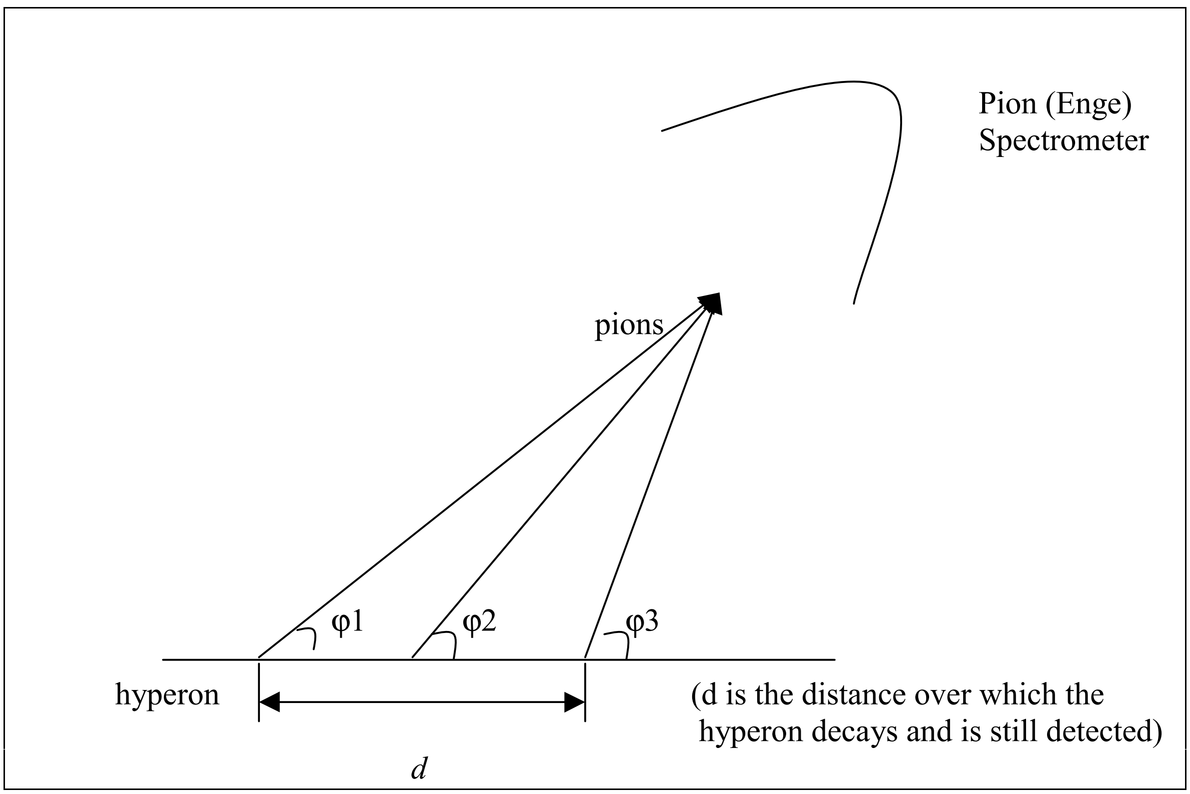


Figure 21. The Λ-hyperons decay all along the path from the point of creation. The decay products (shown here for one spectrometer only) are detected at all the angles as shown that are allowed by the experimental setup. The momenta of the decay products do not change noticeably for all of the decay angles. For the hyperon momentum at threshold for the weak production reaction, the distance *d* shown is roughly 7.7 cm before e^{-1} of them will have decayed.

The Λ-hyperon produced in the reaction will have a momentum of 0.194 GeV/c at threshold for the reaction. The hyperon total energy is 1.132 GeV/c2, has a velocity β=0.1714. At this velocity, e^{-1} of the hyperons decay in 7.77 cm. The decay pions and protons decay in a range of correlated angles, with approximately the same momenta for each angle. These all are detected in the Enge Split Pole and HKS spectrometers, respectively. In this case, the splitter magnet is turned off, but can remain in place in the Hall.

Background positive-helicity events

Not all of the positive helicity events will be due to the weak production reaction of interest; they will not be due, therefore, to neutrino production and will not provide information on the neutrino mass. The incident electron beam polarization will not be 100%, but more like 80%. About 20% of the negative helicity events will be positive-helicity background events. These events can be identified as follows. The events due to zero-momentum neutrinos will be in the few bins in the center of the missing mass spectrum. The positive helicity events due to backgrounds will be evenly distributed over the entire missing mass spectrum. For large neutrino momenta, one gets the background positive-helicity events. Both of these types of events will lie within the acceptance.

Random coincidences

The most significant background contribution will come from random coincidences of protons and pions. Experience with E89-009 shows that this proposed experiment can expect singles rates in the Enge spectrometer of up to 1 MHz and in the HKS of approximately 800 kHz when a 30 μA incident electron beam is incident upon the 1-cm CH_2 target. The coincidence rate (counts per second) expected is given by

$$\text{yield} = \text{luminosity } (\text{cm}^{-2}\ \text{s}^{-1})\ x \text{ cross-section } (\text{cm}^{2}\ \text{sr}^{-1})\ x \text{ acceptance (sr) } x \text{ efficiencies.}$$

The luminosity will be approximately 10^{38} cm^{-2} s^{-1} while the cross section used is $6x10^{-39}$ cm^{2} sr^{-1}. Note that this is approximately one-third of the maximum cross section expected from the published calculations (see Fig. 6). It is important to note that the particles detected (the pion and proton from the Λ-hyperon decay) are correlated; once one is detected, the other is constrained in kinematics. This is important in calculating the spectrometer acceptances in the coincidence experiment. Only the smaller of the two single arm acceptances needs to be used. Thus an experimental acceptance of 10 msr is used in the calculation. The efficiencies include the following: tracking efficiency in both arms (85%), hyperon decay branching ratio (64%), hodoscope detection efficiency in both arms (95%), computer live-time (95%), and Cherenkov detector efficiency in HKS (90%). Thus a total efficiency for the yield calculation is approximately 0.4. Taken together, the numbers indicate that an integrated yield for coincidences from reaction (1) is approximately 50 counts per hour. In a two week-long run, approximately 3% statistics will be achieved for negative helicity events. This will be the very first time that such a measurement has been made. Approximately 10-15 positive-helicity counts will be observed for a 0.5 eV/c^2 neutrino mass.

An estimate of the accidental (*accid*) to real (*real*) coincidence rate may be obtained (crudely) from

$$\frac{accid}{real} = \frac{R_{HKS} R_{Enge} \tau}{R_{coin}} \frac{1}{df} \tag{16}$$

where R represents the singles rates in the numerator and the expected coincidence rate in the denominator of (16), τ is the resolving time, and the duty factor (*df*) is 1. Using conservative estimates of the HKS proton singles rate (~ 10 kHz), the Enge pion singles rate (~700 Hz) and an offline resolving time of 800 ps yields an accidental to real rate of roughly <u>one to one or better</u>. Note that the accidental coincidences will occupy the entire time window (a flat missing mass spectrum for example), while those real coincidence events will reconstruct the narrow Λ peak in just a few bins; the peak will stick out well above the background in this case. This will be simulated in the full proposal for later submission.

The experiment will use the standard Hall C data acquisition system (CODA) and analyzer appropriate for the HKS experiment already approved. The data rates will be approximately the same in both experiments. Additionally, this experiment will provide valuable calibration data for the approved HKS experiment.

Again, it is emphasized that the proposed experiment is compatible with approved Jefferson Lab Experiment E01-011. The ratio of beam energy to splitter magnet and spectrometer settings is identical. The simulations and performance specifications are already presented in a separate document and not repeated here.

The requested resources needed are summarized in Table IV.

Table IV: Requested Resources

beam energy	0.1940 GeV
beam current	25 microamperes
beam polarization	80% (or highest available)
negative hadron spectrometer	Enge Split-pole
negative pion spectrometer setting	0.130 GeV/c
positive hadron spectrometer	HKS
proton spectrometer setting	0.075 GeV/c
Target	CH_2 (solid target, 1-cm thick)
beam time request	15 days

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Collaborators

This experiment will be a part of the new Center for the study of the Origin and Structure of Matter (COSM). COSM is one of only four Physics Frontiers Centers awarded by the National Science Foundation during the first year of competition. It is expected that several other universities will join the collaboration to perform this experiment, in addition to the current members of the COSM collaboration.

Hampton University
Florida International University
Norfolk State University
North Carolina A&T State University